A Huge Drop in X-ray Luminosity of the Non-Active Galaxy RX J1242.6–1119A, and First Post-Flare Spectrum – Testing the Tidal Disruption Scenario

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ABSTRACT

In recent years, indirect evidence has emerged suggesting that many nearby non-active galaxies harbor quiescent supermassive black holes. Knowledge of the frequency of occurrence of black holes, of their masses and spins, is of broad relevance for studying black hole growth and galaxy and AGN formation and evolution. It has been suggested that an unavoidable consequence of the existence of supermassive black holes, and the best diagnostic of their presence in non-active galaxies, would be occasional tidal disruption of stars captured by the black holes. These events manifest themselves in form of luminous flares powered by accretion of debris from the disrupted star into the black hole.

Candidate events among optically non-active galaxies emerged in the past few years. For the first time, we have looked with high spatial and spectral resolution at one of these most extreme variability events ever recorded among galaxies. Here, we report measuring a factor ~ 200 drop in luminosity of the X-ray source RX J1242–1119 with the X-ray observatories *Chandra* and *XMM-Newton*, and perform key tests of the favored outburst scenario, tidal disruption of a star by a supermassive black hole. We show that the detected "low-state" emission has properties such that it must still be related to the flare. The power-law shaped post-flare X-ray spectrum indicates a "hardening" compared to outburst. The inferred black hole mass, the amount of liberated energy, and the duration of the event favor an accretion event of the form expected from the (partial or complete) tidal disruption of a star.

Subject headings: galaxies: individual (RXJ1242.6–1119) — galaxies: nuclei — X–rays: galaxies

1. Introduction

The X-ray luminous nuclei of active galaxies (AGN) are believed to be powered by accretion of gas onto supermassive black holes. There is now growing evidence that many nearby *non-active* galaxies harbor quiescent, weakly or non-accreting black holes (see reviews by Kormendy & Gebhardt 2001; Richstone 2002). Studies of the abundance of black holes, of their masses and their spins, shed light on the mechanisms of black hole growth and of galaxy and AGN formation and evolution. Possibly the most direct means of detecting supermassive black holes at the centers of galaxies, and an unavoidable consequence of their existence, would be occasional tidal disruption of stars and subsequent accretion of their debris by these supermassive black holes (e.g., Hills 1975; Gurzadyan & Ozernoi 1979; Carter & Luminet 1982; Rees 1988, 1990; Wang & Merritt 2004). The events would appear as luminous flares of radiation emitted when the stellar debris is accreted by the black hole.

Stellar capture and disruption is – apart from accretion of gas and black hole merging – one of the three major processes studied in the context of black hole growth (e.g., Frank & Rees 1976). The relative importance of these three processes in feeding black holes is still under investigation. Zhao, Haehnelt, & Rees (2002) and Merritt & Poon (2003) recently pointed out that tidal capture may play an important role in explaining the notable $M_{\bullet} - \sigma$ relation of galaxies. Given the intense theoretical attention the topic of stellar tidal disruption receives (see §3 of Komossa 2002, and references therein), it is of great interest to see whether these events do occur in nature, and how frequent they are.

Making use of the unique capability provided by the All-Sky Survey (RASS, Voges et al. 1999) of the X-ray satellite *ROSAT*, giant X-ray flares from the directions of a few nearby galaxies were discovered (Komossa & Bade 1999; Komossa & Greiner 1999; Grupe et al. 1999; Greiner et al. 2000). These flares were characterized by huge peak X-ray luminosities reaching $\sim 10^{44}$ ergs s^{-1}, large amplitudes of decline, ultrasoft X-ray spectra, and absence of Seyfert activity in ground-based optical spectra (see Komossa 2002 for a review). The target of the present study, RX J1242–1119, was first detected by *ROSAT* in 1992 (Komossa & Greiner 1999) during a pointed observation with the Position Sensitive Proportional Counter (PSPC). At that time it showed a very soft X-ray spectrum with $kT_{\rm bb} \simeq 0.06$ keV, and an X-ray luminosity of $L_{\rm x} \simeq 9 \times 10^{43}$ ergs s^{-1}, which is exceptionally large given the absence of any signs of Seyfert activity of RX J1242–1119 in ground-based (Komossa & Greiner 1999) and *Hubble Space Telescope* (*HST*, Gezari et al. 2003) optical

spectra. The association with one of the two, previously unstudied non-active galaxies at redshift $z = 0.05$ located in the X-ray position error circle (named RX J1242–1119A and RX J1242–1119B for lack of a better designation) however, remained uncertain because of the large *ROSAT* positional uncertainty, in this case $40''$ (Figure 1).

Considering the extraordinary properties of this and a few similar X-ray events, particularly their enormous luminosity output, it is of utmost importance to understand what is happening in these systems. For the first time, we have now looked at one of these flare events with high spatial and spectral resolution, in order to confirm the counterpart, follow the long-term temporal behavior, study the spectral evolution and measure the post-flare spectrum, and to use these results to test the favored outburst model: tidal disruption of a star by a supermassive black hole. Among the few known X-ray flaring galaxies, RX J1242–1119 was our target of choice for follow-up X-ray observations because it flared most recently, so the probability of catching the source in the declining phase was highest. Also, because there were two galaxies in the *ROSAT* X-ray error box, the correct counterpart needed to be confirmed. A Hubble constant of 50 km s^{-1} Mpc^{-1} is used throughout this paper.

2. Data Reduction and Results

2.1. *Chandra*

We observed the field of RX J1242–1119 with the Advanced CCD Imaging Spectrometer (ACIS-S) instrument on-board the *Chandra X-ray Observatory* (Weisskopf et al. 2002) for 4.5 ks on 2001 March 9. The X-ray photons from the target source were collected on the back-illuminated S3 chip of ACIS.

The *Chandra* data allow us to locate precisely the counterpart of the X-ray source. We find that the X-ray emission peaks at coordinates R.A.=$12^{h}42^{m}38\overset{s}{.}55$, decl.=$-11^{\circ}19'20\overset{''}{.}8$ (equinox J2000). Within the errors, this position is coincident with the center of the optically brighter of the two galaxies, RX J1242–1119A (Figure 1). An offset in position of $\approx 1''$ in R.A. can be traced to residual uncertainties in the absolute pointing accuracy of the X-ray telescope. Neither *Chandra* nor *XMM-Newton* detected any other X-ray source within the *ROSAT* X-ray position error circle, including from the optically fainter galaxy RX J1242–1119B.

We do not find evidence for significant source extent. The photons detected by *Chandra* from RX J1242–1119A fall within a radius of $1''$, and the radial profile is consistent with a point source. This indicates that we are still seeing late-phase flare-related emission rather than persistent, extended X-ray emission originating from the host galaxy itself.

A further result, immediately obvious upon inspection of the *Chandra* data, is the huge drop in X-ray flux of RX J1242-1119 compared to its last observation by *ROSAT*. Only 18 source photons were detected by *Chandra*; the implied amplitude of variability is quantified below.

2.2. *XMM-Newton*

Given the strong indications, based on the *Chandra* observation, that the X-ray emission from RX J1242–1119A is still flare-dominated, we asked for a target-of-opportunity observation with *XMM-Newton* in order to obtain, for the first time, a good-quality X-ray spectrum of one of the flaring sources, and to follow the long-term spectral evolution before the source had declined to non-detectability. While the strength of *Chandra* is its high spatial resolution of better than $1''$, *XMM-Newton* has higher throughput (the 18 source photons registered with *Chandra* do not allow spectral fitting).

The *XMM-Newton* (Jansen et al. 2001) observation of RX J1242–1119 was performed on 2001 June 21-22, with a duration of 24.3 ks. Data from the EPIC-pn, MOS1, and MOS2 detectors were used for analysis. The observation was first checked for flares in the background radiation; none were detected. Photons were then extracted from a circular area of radius $0\farcm3$ centered on the target source. For the MOS cameras the background was determined in an annulus around the source with an inner radius of $1\farcm0$ and an outer radius of $3\farcm0$. The background counts for the pn observation were selected in a circular region close to the target source. The total source count rate, measured in the EPIC-pn detector, amounts to 0.0137 counts s^{-1} in the $0.3-5$ keV energy band. No systematic decrease (or increase) of the count rate is present during the observation.

The X-ray *spectrum* yields important information on the physics governing the post-flare evolution. X-ray emission from RX J1242–1119A is detected in all three of the following energy intervals: 0.3–0.75 keV, 0.75–1.5 keV, 1.5–5 keV, with count rates of 0.0073, 0.0040, and 0.0024 counts s^{-1}, respectively. For spectral analysis, source photons were binned such that each spectral bin contains > 25 photons. The resulting spectrum is best described by a power law with photon index $\Gamma_x = -2.5 \pm 0.2$ ($\chi^2_\nu = 1.1$; Figure 2). We do not find evidence for strong excess cold absorption. The absorption towards RX J1242–1119A is consistent with the Galactic value of $N_H = 3.74 \times 10^{20}$ cm^{-2}. Thermal (Raymond-Smith and MEKAL) X-ray emission models yield significantly worse spectral fits if the metal abundance of the X-ray emitting gas is constrained not to fall significantly below 0.1 times the solar value.

Using the best-fitted power-law spectral model, the *XMM-Newton* “low-state” luminos-

ity of RX J1242–1119 is $L_{\rm x} = 4.5 \times 10^{41}$ ergs s^{-1} in the 0.1–2.4 keV band. Compared to the peak luminosity of 9×10^{43} ergs s^{-1} measured with *ROSAT*, this corresponds to a factor ≈ 200 decline.

Finally, we used the Optical Monitor (OM) data to estimate the B and U magnitudes of RX J1242–1119A (and B). The OM observations were performed in standard image mode, with U, B, and two broad-band UV filters. Five high- and one low-resolution image per filter were collected with an exposure time of 1000 s each. The data files were processed with *sas 5.4.1* and with the task *omichain* to perform required corrections for tracking, bad pixels, fixed pattern, and flat-field. Both galaxies are detected in the U, B, and $UVW1$ filter bands, and their angular separation is large enough to avoid confusion. Total source counts were measured for each galaxy in an aperture radius of 12 pixels as recommended to account for the broad wings of the OM point-spread function. Corrections for coincidence losses and dead-time were applied to the total count rates, and then background was subtracted. A mean corrected count rate was then computed for each filter band. To estimate the magnitudes, the most recent zero-point corrections (as of 2003 November) were applied. This yields the following B and U magnitudes for RX J1242–1119A(B): $m_B = 17.56 \pm 0.05(18.72 \pm 0.06)$ mag and $m_U = 17.80(18.83)$ mag.

3. Discussion

We have utilized the complimentary abilities of the X-ray observatories *Chandra* and *XMM-Newton* to study the peculiar *ROSAT* source RX J1242–1119. With *Chandra*, we found that the source of the bright X-ray emission detected by *ROSAT* is the galaxy RX J1242–1119A. The flare emission has declined dramatically by a factor of ≈ 200, but has not yet faded away completely. *XMM-Newton* then provided us with the best post-flare spectrum ever taken of any of the few flaring, optically inactive galaxies. The spectrum is of power-law shape; there is no evidence for excess absorption, and the post-flare spectrum is harder than the flare maximum.

There is an additional argument that the detected point-like low-state X-ray emission does not arise from the ISM of the host galaxy, but is related to the mechanism that produced the flare itself. Compared with the blue luminosity of RX J1242–1119A, inferred from the extinction-corrected blue magnitude $m_{B,0} = 17.43$ mag measured with the OM, the X-ray emission of this galaxy is still very high, even in its low state. Its ratio of X-ray to blue luminosity, $\log{(L_{\rm x}/L_B)} \approx 31.6$, is above the upper end observed so far for field early-type galaxies (Irwin & Sarazin 1998; O'Sullivan et al. 2001).

While the X-ray observations presented here demonstrate that the post-flare emission is associated with the galaxy RX J1242–1119A, it was established previously that the optical spectrum of RX J1242–1119A is that of a non-active galaxy (Komossa & Greiner 1999, Gezari et al. 2003). In addition to other arguments presented earlier, the absence of any significant excess X-ray absorption above the Galactic value argues against the scenario of an extremely X-ray variable active galactic nucleus that is completely obscured optically. We find that the galaxy RX J1242–1119A is not detected in the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) at 1.4 GHz, also consistent with the absence of a *permanent* (hidden) active nucleus.

The X-ray observations reported here place important constraints on the total duration of the flare maximum. The source was not detected in 1990 in a short exposure during the RASS. It was "on" in 1992, and had dropped dramatically in flux during the *Chandra* and *XMM-Newton* observations in 2001, limiting the "on-state" to ≤ 10 yr. The high outburst luminosity and amplitude of variability strongly suggest that a supermassive black hole at the center of RX J1242–1119A is the ultimate power source. The new observations presented here are consistent with and corroborate the previously favored tidal disruption scenario to explain this flare event.

Independent of the X-ray properties of RX J1242–1119A, its blue magnitude measured by the OM can be used to estimate the mass of the black hole at the center of the galaxy. The correlation between the absolute blue magnitude of the bulge of an elliptical galaxy and the mass of the central black hole (Ferrarese & Merritt 2000) predicts a black hole mass of $\approx 2 \times 10^8\,M_\odot$. This estimate is uncertain by a factor of several, given the scatter in the relation between bulge luminosity and black hole mass (e.g., Ferrarese & Merritt 2000, McLure & Dunlop 2002). The observations are consistent with either partial disruption of a giant star, or complete disruption of a solar-type star[1], where either only part of the debris from the solar-type star is accreted while the rest becomes unbound, or where part of the debris is accreted in a radiatively inefficient mode.

To estimate (a lower limit on) the amount of stellar debris accreted by the black hole, we forced the high-state and low-state luminosities to follow a $t^{-5/3}$ law expected for the "fall-back" phase (e.g., Rees 1990; Li et al. 2002) of tidal disruption. The integral $\int L(t)\,dt$ then gives the total emitted energy, $E \simeq 1.6 \times 10^{51}$ ergs, where we started the integration at the time the source was first observed in the high-state by *ROSAT*. This requires accretion

[1]the latter only if the tidal radius is located outside the Schwarzschild radius, i.e., for $M_{\rm BH} \lesssim 10^8\,M_\odot$ (e.g., Hills 1975); or for larger black hole masses, if the black hole is of Kerr type and the star approaches from a favorable direction (Beloborodov et al. 1992)

of $M \simeq 0.01\,\eta_{0.1}^{-1}\,M_\odot$ of stellar material, where $\eta = 0.1\,\eta_{0.1}$ is the efficiency.

Although the X-ray emission of RX J1242–1119A dropped substantially, does this necessarily mean that the *total* accretion luminosity declined, or is it possible that the emission just shifted out of the X-ray band? Part of the flux may have softened into the unobservable EUV part of the spectrum, as expected in some tidal disruption models (e.g., Cannizzo et al. 1990), but it is more likely that the total luminosity has declined since outburst. Otherwise, we might expect to see optical emission lines excited by the hypothesized bright EUV continuum; such emission lines do not appear in *HST* spectra of RX J1242–1119A taken several years after the outburst (Gezari et al. 2003).

With all observational tests possible now performed, more detailed comparison with theory has to await refined model calculations of stellar disruption.

4. Concluding Remarks

The results presented here demonstrate the effectiveness of combining the abilities of the two most powerful X-ray observatories in orbit to study one of the most extreme variability events ever recorded among galaxies. In our interpretation of these observations, we are seeing the post-disruption phase of a close encounter of a star with a central supermassive black hole, into which some of the tidal debris is accreting. Continued X-ray monitoring of RX J1242–1119A will enable us to follow the expected further decline in luminosity.

Future X-ray (all)-sky surveys planned for missions like *DUO*, *ROSITA*, *LOBSTER*, and *MAXI* will be very useful in finding new flare events, while their detailed study will become possible with future high-throughput X-ray missions like *XEUS* and *Con-X*. We may then be able to probe the regime of strong gravity, since the temporal evolution of the flare X-ray emission is expected to depend on relativistic precession effects in the Kerr metric.

The results presented here will impact further model calculations of the tidal disruption process, which are still complex and challenging, and are expected to motivate new studies of the flare host galaxies as well as an expanded search for similar flare events in existing and future *Chandra* and *XMM-Newton* archives, including the deep fields.

Such observations of flares open up a new window to study supermassive black holes and their environment, and the physics of accretion events in otherwise inactive galaxy nuclei.

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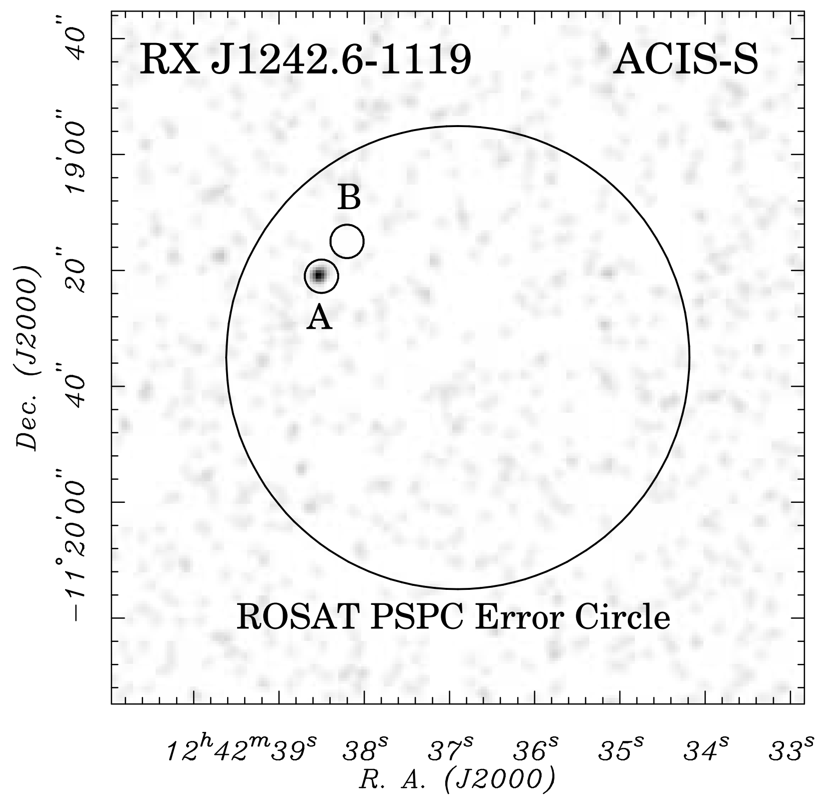

Fig. 1.— *Chandra* X-ray image of the area around RX J1242–1119A. The *large circle* corresponds to the *ROSAT* error box, while the two *small circles* mark the optical positions of the two galaxies RX J1242–1119A and B.

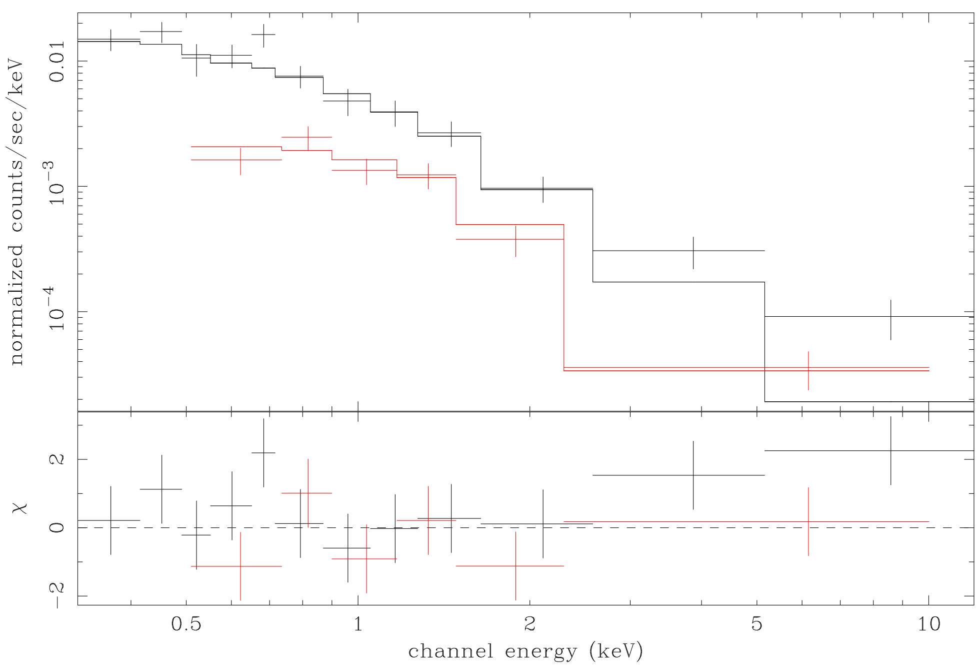

Fig. 2.— *XMM-Newton* X-ray spectrum of RX J1242–1119, and best-fitted power law model (*solid lines*). *Upper symbols*: EPIC pn data. *Lower symbols*: MOS 1 and 2 data binned together.